LEVEL (12)

NAVAL AIR ENGINEERING CENTER

REPORT NAEC-92-128

LAKEHURST, N.J.
08733

(6)

FEASIBILITY EVALUATION OF ADVANCED EDDY CURRENT INSPECTION EQUIPMENT FOR USE IN NAVAL AVIATION MAINTENANCE ENVIRONMENT.

Handling & Servicing/Armament Division
Ground Support Equipment Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

D D C

OCT 18 1978

F

(11)   28 Sept   978

(12) 37p.

(15) N68335-77-C-1116

(9) Final Report,   18 July 1977—16 Feb   978.
A3400000/051B/8F41461406

(10) Robert P./Meister Stephen D./Brown

APPROVED FOR PUBLIC RESEASE:
DISTRIBUTION UNLIMITED

(18) NAEC 92-128

(19)

Prepared for

Commander, Naval Air Systems Command
AIR-340E
Washington, D.C. 20361

78 10 10 07

407 080

FEASIBILITY EVALUATION OF ADVANCED
EDDY CURRENT INSPECTION EQUIPMENT FOR USE
IN NAVAL AVIATION MAINTENANCE ENVIRONMENT

Prepared by: _Robert P. Meister_

Robert P. Meister

Stephen D. Brown

Stephen D. Brown

Reviewed by: _Richard C. Deitrich_

Richard C. Deitrich
Advanced Technology Section, Handling
and Servicing/Armament Division (927)

Approved by: _F. E. Evans_

for

F. E. Evans
Ground Support Equipment Superintendent

NOTICE

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NAEC-92-128	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FEASIBILITY EVALUATION OF ADVANCED EDDY CURRENT INSPECTION EQUIPMENT FOR USE IN NAVAL AVIATION MAINTENANCE ENVIRONMENT		5. TYPE OF REPORT & PERIOD COVERED FINAL 18 July 1977 - 16 Feb 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Mr. Robert P. Meister Mr. Stephen D. Brown		8. CONTRACT OR GRANT NUMBER(s) N68335-77-C-1116
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle Columbus Laboratories 505 King Avenue Columbus, OH 43201		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS A3400000/051B/8F41461406
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command AIR-340E Washington, DC 20361		12. REPORT DATE 28 September 1978
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Air Engineering Center Ground Support Equipment Dept. (Code 92724) Lakehurst, NJ 08733		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

multifrequency   advanced signal processing
ultra-low frequency   adaptive learning methods

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Presents Phase I of a three phase program to develop a general eddy current system incorporating advanced eddy current signal processing. Phase I describes feasibility and applications for general system requirements such as (1) capability to cover broad spectrum of materials (2) incorporation of advanced eddy current concepts in a system operable by relatively unskilled operators.

SUMMARY AND CONCLUSIONS

This report documents the results of Phase I of a three phase program whose ultimate objective is to develop a general purpose eddy current system (GPECS) for use in Naval Air Rework Facilities (NARF) and Aircraft Intermediate Maintenance Departments (AIMD) maintenance facilities. Phase I objectives were to establish the feasibility of an eddy current system for general purpose usage incorporating advanced eddy current signal processing concepts such as multifrequency eddy current (MFEC). General system requirements are (1) the capability to cover a broad spectrum of materials and test applications and (2) incorporation of advanced eddy current concepts in a system operable by relatively unskilled operators.

Existing NARF and AIMD eddy current maintenance applications are reviewed, and areas where existing eddy current nondestructive evaluation (NDE) capability exhibits shortcomings are identified. In addition, potential future applications based on use of advanced multifrequency eddy current (MFEC) technology can be identified.

A demonstrated methodology for use in designing eddy current tests and probes is identified. Computer programs designed originally for eddy current nuclear applications offer the capability to perform parametric studies between test coil excitation frequency and coil design for NAVAIR applications.

Examples of previous Battelle-Columbus applications of MFEC signal processing are given. MFEC technology has successfully been integrated in many Battelle-Columbus developed systems. Recent design and construction of a digital MFEC system for Air Force maintenance applications for use by flight-line personnel demonstrate the feasibility for similar NAVAIR functions.

Phase II and Phase III approaches are outlined and based on successful Battelle-Columbus utilization of MFEC technology; the Phase II program is recommended.

ACCESSION for

NTIS	White Section
DDC	Buff Section ☐
UNANNOUNCED	☐
JUSTIFICATION	

BY
DISTRIBUTION/AVAILABILITY CODES

	AIL. and/or SPECIAL
A	

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The U.S. Navy is interested in procuring state-of-the-art nondestructive testing (NDT) equipment for general purpose use in maintenance facilities. The eddy current method has potential of using advanced signal processing techniques which can be integrated into a general portable inspection unit. This eddy current system would be capable of utilizing a variety of eddy current probes, data acquisition, and signal processing techniques to inspect a spectrum of materials in applications involving the detection of defects and measurement of properties critical to aircraft performance. These applications include, but are not limited to, crack detection, conductivity measurement, fiber/matrix analysis, sorting of parts, thickness measurement, and measurement of nonconducting coatings on metallic substrates. Development of a general purpose eddy current instrument would incorporate the latest electronic equipment such as small digital computers to simplify equipment operations as well as provide flexibility in the performance of mechanical and signal processing functions.

A three-phase program is suggested to achieve the desired general purpose eddy current instrument development. This report describes the results of Phase I.

II. PROGRAM OBJECTIVES

A. The objective of Phase I is to evaluate the feasibility for development of an advanced, general purpose eddy current inspection system for use in the Naval aviation maintenance environment. The eddy current system shall have the capability of performing state-of-the-art inspections utilizing advanced techniques such as multifrequency eddy current (MFEC) and providing the necessary devices and functions which will simplify and otherwise assist operators in performing instrument calibration, initialization, and manipulation of test probes and coils.

B. The Phase II objectives are to develop a laboratory breadboard model of the general purpose eddy current instrument and critically assess its capability via a series of controlled experiments realistic of anticipated NAVAIR maintenance applications.

C. Phase III objectives are to develop a production prototype instrument for evaluation and use in the NAVAIR maintenance environment.

III. PHASE I EFFORTS

A. DESCRIPTION. The Phase I effort consists of four tasks:

Task 1 - Review existing and potential NAVAIR eddy current inspection requirements.

Task 2 - Define the general purpose eddy current system (GPECS) requirements and suggest means by which these requirements can be met.

Task 3 - Describe a GPECS configuration and outline the Phase II project for the development and evaluation of a laboratory GPECS model.

Task 4 - Outline the Phase III project for the development and evaluation of a field prototype GPECS.

B. TASK 1 - INSPECTION REQUIREMENTS. On-site visits to the Naval Air Rework Facility, Jacksonville (NARF JAX) and the NAS Cecil Field Aircraft Intermediate Maintenance Department (AIMD) were conducted by Battelle-Columbus staff members. The purpose of the visits was to review present NDT operations at these two typical Navy aircraft maintenance facilities, representing two maintenance levels, to assist in the formulation of plans for the development of an advanced general purpose eddy current inspection system.

1. NARF BACKGROUND INFORMATION. The NARFs are similar in many respects to the Air Force's Air Logistic Commands, the equivalent depot level maintenance organizations which project personnel have previously visited. There are six NARFs. NARF JAX employs about 3,000 people. Some NARFs are larger, e.g., North Island is about twice as big. The NARFs are assigned responsibilities for cognizance over certain aircraft. NARF JAX has cognizance over specific aircraft types, the A-7, RA-5C, and P-3. They maintain, rebuild, or modify all components of the aircraft. The NARF does tear down, modification, and repair on a scheduled basis; for example, 36 months for the A-7. Certain parts are maintained more frequently.

a. NARFs get involved with other aircraft when the cognizant NARF work load is too heavy. They may also provide assistance to the Air Force when necessary or desirable.

b. Each NARF is responsible for developing and promulgating the NDI procedures for the aircraft they have cognizance over. Few aircraft have an inspection manual prepared by the manufacturer. The A-7, however, does have a manual which was prepared by a cooperative effort of Navy, Air Force, and manufacturer. This manual has a number of inspections which cover what designers thought were critical areas. However, as experience has shown some of these areas to be trouble-free, the routine inspection of the areas has been deleted.

c. The maintenance inspection requirements are largely based on reaction to identified problems. When a failure occurs in an aircraft, the Materials Testing people analyze the failure and take appropriate action to inspect similar aircraft in the failure-prone area.

d. NARF JAX uses eddy current (and ultrasonic) tests quite extensively. They employ radiography to a lesser extent than expected based on previous Battelle-Columbus involvement with DOD aircraft inspection operations. It was stated that other NARFs may not use eddy current and ultrasonic tests as extensively as NARF JAX.

e. NDI technicians/inspectors are typically trained in industrial training schools, for example, Magnaflux or Automation Industries. They may have had prior experience in military or may have started as a helper and been trained to achieve higher job ratings.

f. NARF JAX has the following eddy current instruments: Nortec NDT 3, Nortec NDT 5, Nortec NDT 6, Dermitron, and Magnaflux ED 520. The Magnaflux ED 520 is the standard issue eddy current unit throughout NAVAIR. Each AIMD normally has only an ED 520, and this unit is the norm for all testing operations. The NARFs use the other units to set up procedures.

g. A major problem with current eddy current instruments, according to NARF personnel, is their lack of resolution in measuring conductivity at the low end of the scale. Most new engine materials have very similar conductivity values and eddy current instruments are needed to differentiate between the materials based on small conductivity differences.

h. Another major problem is lack of suitable standards or time to make suitable standards. Each application requires having a standard very similar to the test part. Often the person requesting the test does not allow time to make this standard. This is a continuing problem in all NDT and probably cannot be completely solved. It is particularly difficult in eddy current testing since there are so many variables that affect test response, and these must be duplicated fairly exactly in the standard.

i. Application areas for eddy current are:

● Detection of Surface Cracks

(1) Almost exclusively inside bolt holes and in radiused areas; used extensively for landing gear and pylons.

(2) Verification of indicated cracks detected during dye penetrant test.

● Materials Sorting

(1) Identify types of plasma spray coatings on engine parts, for example, whether Ni or Co base to determine what stripping operation should be used.

(2) Detect heat-damaged areas in aircraft structure and in wheels.

● Hard Coatings. Have not had to measure case depth or surface hardness on case hardened parts. They have been asked to measure thickness of a hard coating on valve stems, but were unable to do so.

8

j. A couple of instances were mentioned where the ED 520 was judged unsuitable for present needs.

(1) Personnel have used the NDT 3 with a differential probe to inspect for cracks in threaded areas. The ED 520 is not a differential test unit.

(2) NARF Pensacola uses a Magnaflux ED 800 unit for finding corrosion in the second layer. This is a new unit which is similar to the NDT 6, but has a memory capability so that a standard signal can be retained for direct comparison with the test signal. It is believed other units, for example, the NDT 6, could be used for this test, but the memory system probably is very handy in making interpretations of results.

2. AIMD BACKGROUND INFORMATION. There are numerous AIMDs. This is the maintenance level for which the eddy current equipment being developed on this program is intended. Each air station and aircraft carrier has one. The AIMD conducts standard inspections according to the aircraft's manual and bulletins. These inspections are typically done on the aircraft and do not involve teardown for removal of the parts.

a. Cecil Field AIMD personnel are innovative in making the best possible contribution to overall inspection programs; they are not afraid to tackle new problems and to look for ways to be most effective, for example, they inspect circuit boards radiographically to eliminate tedious microscopic examinations. Major eddy current use is in inspecting wheels for heat damage and for flaws in the flange, bead, and valve areas. Fixtures are used to perform the inspections efficiently. There were complaints about the inadequacy of the ED 520 meter readout. Acquisition of an ED 800 is under way because of the advantages of the oscilloscope screen readout and the memory feature of the instruments.

b. Although the Battelle visits represent only one of six NARFs and one of many more AIMDs, extrapolation of the previous observation to other NARF and AIMD operations can be made bearing in mind the relative NDT capabilities of the Jacksonville facilities. The major conclusions from the visits are summarized in Table 1, page 10.

c. Although the extent of presently used eddy current application is rather limited, with advanced instrumentation bringing the facilities up to current state-of-the-art in the areas of (1) ultra-low frequency testing, e.g.. 10 Hz and (2) advanced data processing and analysis, the application areas can be greatly expanded. Improved capabilities in (1) quantitative testing of materials properties such as hardness (strength), (2) depth of penetration for subsurface characterization where advantages of the energy field/material geometry interaction peculiar to the eddy current method can be beneficially employed, and (3) inspections of components in relatively inaccessible locations, for example, engine components where the advantages of small eddy current probes and lack of coupling requirements can be employed, will open a vast number of inspection applications to the eddy current method.

TABLE 1 - COMPARISON OF PRESENT EDDY CURRENT TECHNOLOGY OF NARF AND AIMD

	NARF	AIMD
Technology Functions	Develop procedures. Develop coils, fixtures. Some applied research on problems.	• Apply procedures. • Improve developed procedures using application experience.
Technical Expertise	Equivalent to Level III ASNT TC-1a.	• Equivalent to Level I or Level II ASNT TC-1a.
Inspection Functions	On parts which are removed during major tear-down for maintenance.	• In-situ on airplane. • On parts which are readily/regularly removed.
Equipment	Many types of standard NDT units.	• One or two standard NDT units.
Applications	• Surface cracks in places difficult to inspect by ultrasonics or other methods, e.g., in and adjacent to bolt holes on pylons and landing gear. • Heat damage. • Material sorting.	• Heat damage. • Surface cracks.

d. Based upon these observations and conclusions regarding NARF/AIMD capabilities and responsibilities the general purpose eddy current system (GPECS) should have certain attributes:

• It should be versatile enough to be used on a large variety of applications that may appear at the NARF level.

• It should have advanced signal processing capabilities required to analyze problems and develop procedures at the NARF level.

• It should be simple enough to be used by Level I qualified personnel at the AIMD level following procedures developed by the NARF personnel.

In reviewing existing NARF and AIMD eddy current maintenance use, additional potential applications were identified. For initial GPECS definition, these applications are summarized in Table 2, page 11, and in general include the maintenance applications identified in Table 1. A myriad of applications is included in Table 2 and further detailed study is necessary prior to placing bounds on GPECS parameters.

TABLE 2 - POTENTIAL APPLICATION FOR GENERAL PURPOSE EDDY CURRENT SYSTEM

Classification by Purpose	Application	System Design Factors		
		Materials	Occurrence	Environments
A. Defect Detection				
• Cracks	Structure	Aluminum Alloys	Near Surface	In-Situ
Low Cycle Fatigue		Titanium Alloys	Opposite Surface	Disassembled
High Cycle Fatigue		Lo-Alloy Steel	Interlayer	
Stress Corrosion		Composites	Inside Holes	
• Corrosion (Wastage)	Structure	Aluminum Alloys	Interlayer	In-Situ
			Opposite Surface	
• Cracks	Engine	Hi-Temperature Alloys	Near Surface	In-Situ Remote
Low Cycle Fatigue		Titanium		Disassembled
High Cycle Fatigue				
Stress Corrosion				
• Wear	Engine	Hi-Temperature Alloys	Near Surface	Disassembled
B. Thickness Measurements				
• Monolithic	(See Corrosion and Wear)			
• Metal/Metal	Structure	Chrome Plate Steel-Hardened Surfaces	Near Surface	Disassembled
	Engine	Nickel/Cobalt on Hi-Temperature Alloys	Near Surface	Disassembled
C. Lift-Off				
• Nonmetal/Metal	Structure	Paint	Near Surface	Disassembled
	Engine	Ceramics	Near Surface	Disassembled
D. Conductivity				
• Hardness/Strength	Structure	Case Hardness in Steels	Near Surface	Disassembled
		Surface Cold Work in Aluminum and Steel	Near Surface	Disassembled
		Temper of Aluminum Alloys and Steel (Heat Damage)	Near Surface	In-Situ Disassembled
• Residual Stress Gradients	Structure	Aluminum Steel	Near Surface	In-Situ
• Chemical Composition	Structure	Aluminum Steel Titanium	Near Surface	Disassembled
	Engine	Hi-Temperature Alloys	Near Surface	Disassembled

C. TASK 2 - GENERAL SYSTEM REQUIREMENTS. In this section, initial bounds
are placed on the GPECS requirements. The basic eddy current test object
interaction is broken down into more fundamental or functional elements, and
then each is attacked separately.

Figure 1, page 12, illustrates the basic eddy current materials interaction.
From Figure 1, three basic divisions can be identified: (a) eddy current
test/probe design, (b) signal generation/reception and conditioning and, (c)
signal processing and display. In this section we consider the design of an
eddy current test, a rational methodology by which this can be achieved and
demonstrate the advantages of advanced eddy current signal processing con-
cepts. These items will impose requirements on item (b) which is dicussed in
more detail in Task 3.

I		II		III
Eddy Current Test/Probe Design		**Eddy Current Instrumentation**		**Signal Processing and Display**

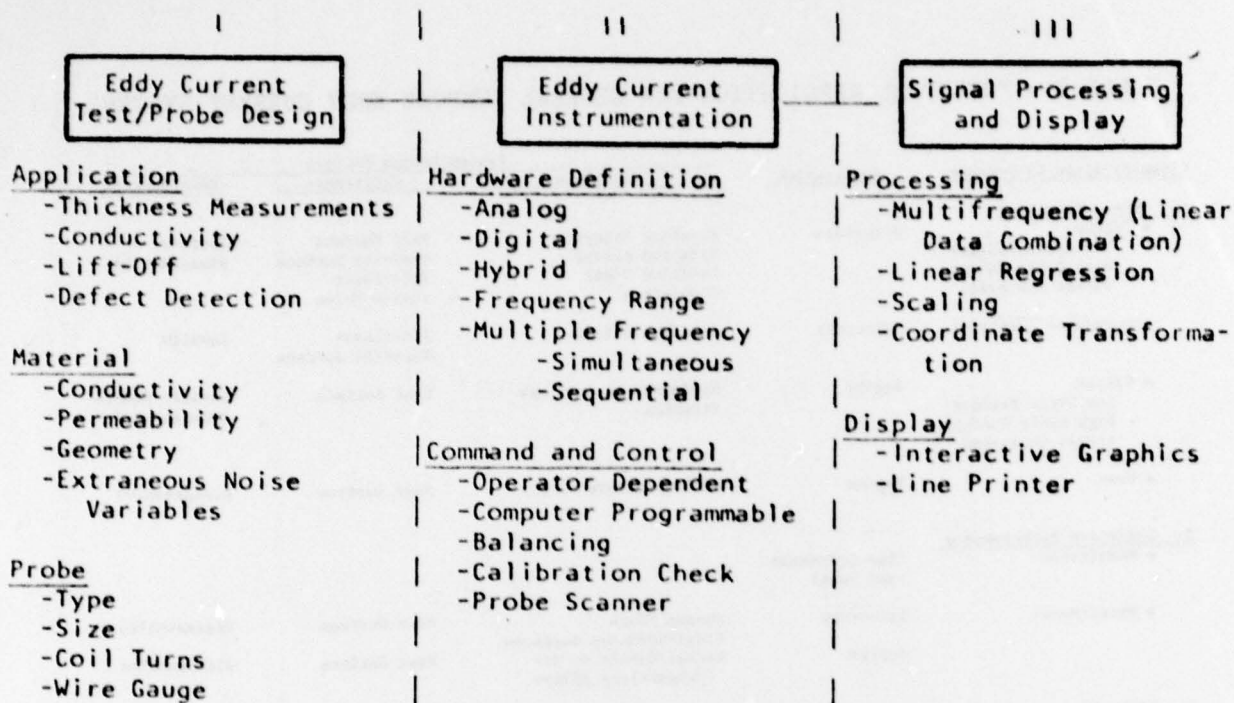| Application	Hardware Definition	Processing
-Thickness Measurements	-Analog	-Multifrequency (Linear
-Conductivity	-Digital	Data Combination)
-Lift-Off	-Hybrid	-Linear Regression
-Defect Detection	-Frequency Range	-Scaling
	-Multiple Frequency	-Coordinate Transforma-
Material	-Simultaneous	tion
-Conductivity	-Sequential	
-Permeability		Display
-Geometry	Command and Control	-Interactive Graphics
-Extraneous Noise	-Operator Dependent	-Line Printer
Variables	-Computer Programmable	
	-Balancing	
Probe	-Calibration Check	
-Type	-Probe Scanner	
-Size		
-Coil Turns		
-Wire Gauge		

FIGURE 1.   BASIC EDDY CURRENT FUNCTIONAL ELEMENTS

1.   EDDY CURRENT TEST/PROBE DESIGN. The test probe or coil serves as the primary link between the eddy current instrumentation and the test object. The coil or coils serve two purposes: (1) to establish a varying electromagnetic field which causes currents to be induced in the adjacent test object and (2) to sense the current flow and magnetic effects within the test object.

a.   The test probe may be excited at a single frequency, or sequentially, or simultaneously at several frequencies in order to obtain information relative to the test object. The choice of frequency or frequencies is a function of material parameters such as conductivity or relative permeability, extraneous noise variables such as surface roughness and intended eddy current test application which generally can be classified into four areas; i.e., thickness measurements, conductivity measurement, measurement of lift-off, and defect detection.

b.   The type of test probe used, that is, absolute, differential, or reflection coil is determined by the test application and material noise variable. In addition, probe size or configuration will be related to test part geometry and in turn can affect eddy current penetration depth within the test object.

c.   It should be apparent at this stage that the choice of probe shape, type, and excitation frequencies is a complex process. Historically, the design of eddy current tests has been guided by experience and

12

experimental trial and error. The optimization of an eddy current test for a particular problem required a series of experiments which quite often were expensive and time consuming.

    d. Rational eddy current test design had been aided greatly by the analytical work of C. V. Dodd, reference (a). Over a period of ten years or so, a sound foundation has been established for the computer aided design of eddy current tests and test coil design. It is the intent to incorporate this methodology into the NAVAIR Phase II program for the efficient design of NAVAIR maintenance eddy current tests and test coil parameters.

    e. As an example, we consider the design of a test for the measurement of the thickness of a single conductor. In this example, we may be interested in the measurement of thickness directly or we can translate the problem into one of detecting corrosion (wall thickness reduction) on the underside of an aircraft wing skin.

● A reflection-type probe is considered for the thickness measurement application and shown in Figure 2, page 14, in the vicinity of a conductor. The reflection probe coil consists of a single large drive coil which is used to induce eddy currents into the test object and two pickup-coils connected in series opposition for monitoring the effects of the eddy current flow. The test parameters of interest are the driver-coil radius and driver-coil excitation frequency.

● If the probe is placed on a single conducting plate, as shown in Figure 2, and the plate thickness is varied by 10 percent, a phase shift will result in the pickup coil voltage. The resultant phase shift is a function of driver coil excitation frequency, plate material conductivity, driver coil size, and plate thickness. The previous group of variables can be classified in a manner that only two independent parameters need be considered. These are (1) the ratio of the plate thickness to drive coil mean radius and (2) the dimensionless product $\omega\mu\sigma\bar{r}^2$, defined as in Figure 3, page 15. Figure 3 shows the resultant phase shift for a 10 percent thickness change versus $\omega\mu\sigma\bar{r}^2$, for various ratios C of plate thickness to mean driver coil radius. From Figure 3, we see that the phase change for a 10 percent thickness change increases, enters a plateau region in which it is essentially constant and finally decreases, as the product $\omega\mu\sigma\bar{r}^2$, increases. The absolute values of phase change are a function of the ratio of initial test object thickness to mean driver coil radius, that is, C in Figure 3. As we can see, the ultimate eddy current test design problem is a function of the material parameter (permeability, conductivity, and thickness), the eddy current system coil excitation frequency, and the test coil mean radius.

● The greatest phase shift results for small values of C which again is the ratio of plate thickness to mean coil radius. The maximum over which the largest phase shift exists is also rather broad which suggests that for a given product of $(\omega\mu\sigma\bar{r}^2)$, the latitude in coil excitation frequency is quite broad.

Ref: (a) Dodd, C. V., "The Use of Computer-Modelling for Eddy Current Testing," Research Techniques in Nondestructive Testing, Vol. 3.
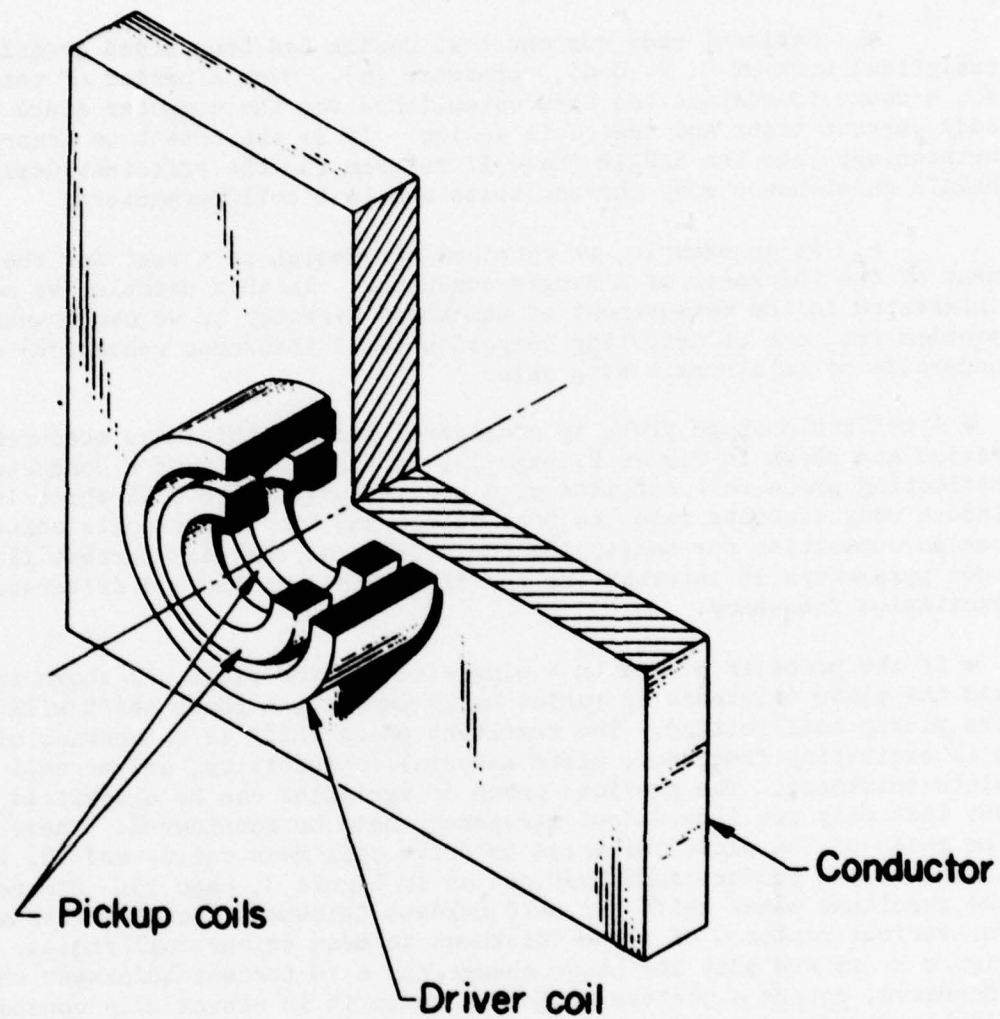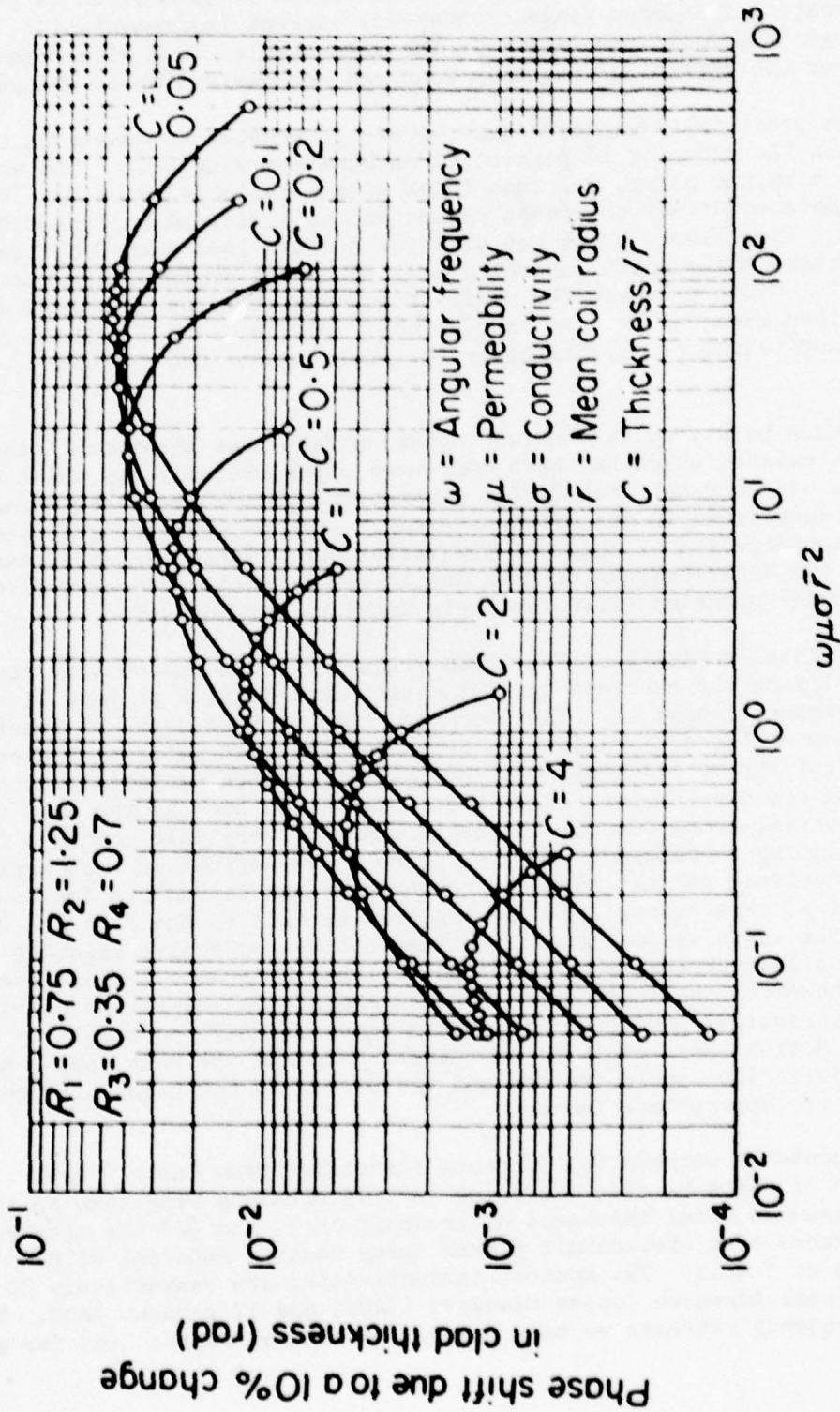
FIGURE 2.   REFLECTION TYPE EDDY CURRENT TEST COIL (a)

FIGURE 3. PHASE SHIFT VERSUS $\omega\mu\sigma\bar{r}^{-2}$ FOR VARIOUS MATERIAL THICKNESS TO COIL RADIUS RATIOS (a)

15

● For a given material thickness, the larger $\bar{r}$ is made, the greater the resultant phase shift, that is, the smaller C becomes. The maximum coil size would be determined by the area of the material it is desired to resolve and the operating frequency range of the eddy current instrumentation. In general, the larger the coil, the larger is the area sampled in a given measurement and the lower the operating frequency required for maximum phase change.

● As a practical example, assume we are interested in measuring a thickness change on the order of 10 percent in an aluminum wing skin. The material is 7075-T6 aluminum alloy, 0.1 inch thick with a resistivity of $2 \times 10^{-6}\,\Omega$ -inch. An estimate of driver coil mean radius and coil excitation frequency is desired. From Figure 3, we see that for C = t/$\bar{r}$ less than 0.2, the increase in resultant phase shift is negligible. Thus the smallest practical value of C is 0.2. Since C equals the ratio of material thickness to mean coil radius, the desired mean coil radius is 0.5 inch. In the C = 0.2 plateau region, we have $\omega\mu\sigma r^2$ equal to approximately 20. Solving for the frequency we obtain 800 Hz.

● At this point, we have tried to demonstrate that a rational analytic approach exists, which has been confirmed experimentally, by which one can estimate eddy current test design parameters. There are other parameters which must be considered in the previous example such as minimizing lift-off effects and an appreciation of conductivity variations. These variables can play a role in the determination of coil design requirements and excitation frequency, and computer programs exist for their detailed consideration.

● An initial estimate of the GPECS frequency range can be best accomplished by identifying the extremes of application from Table 2 on page 11 and making use of Figure 4, page 17. The necessary eddy current depth of penetration is a function of the coil excitation frequency and test material properties such as conductivity or its reciprocal resistivity and the material relative permeability, and the particular test application such as the measurement of gross material properties or the measurement of very thin coatings (such as chrome plating thickness). To use Figure 4, we define our test application, which in essence defines depth of penetration and determines the test material resistivity. Proceeding from the resistivity axis on the left and skin depth axis on the right we draw parallel lines to the respective axis, as shown by the dashed line of Figure 4, until these lines intersect. Where the dashed lines intersect, one then moves downward again parallel to the coordinate axis until the required product of frequency times relative permeability is intercepted. Notice that the lower coordinate axis and the skin depth axis to the right have various scale factors and the arrows to the right of Figure 4 identify the appropriate factor.

● The probable extreme applications identified from Table 2 are: (1) the detection of opposite side corrosion in 7075 aluminum wing-span splice joints with an assumed total thickness of one-half inch, and (2) the measurement of the thickness of nickel-cobalt plasma spray coating material with an assumed thickness of 5 mils. The nominal conductivities are respectively 30 percent International Annealed Copper Standard (IACS) and 17 percent IACS. To estimate GPECS frequency extremes we make use of two general rules: (a) for gross
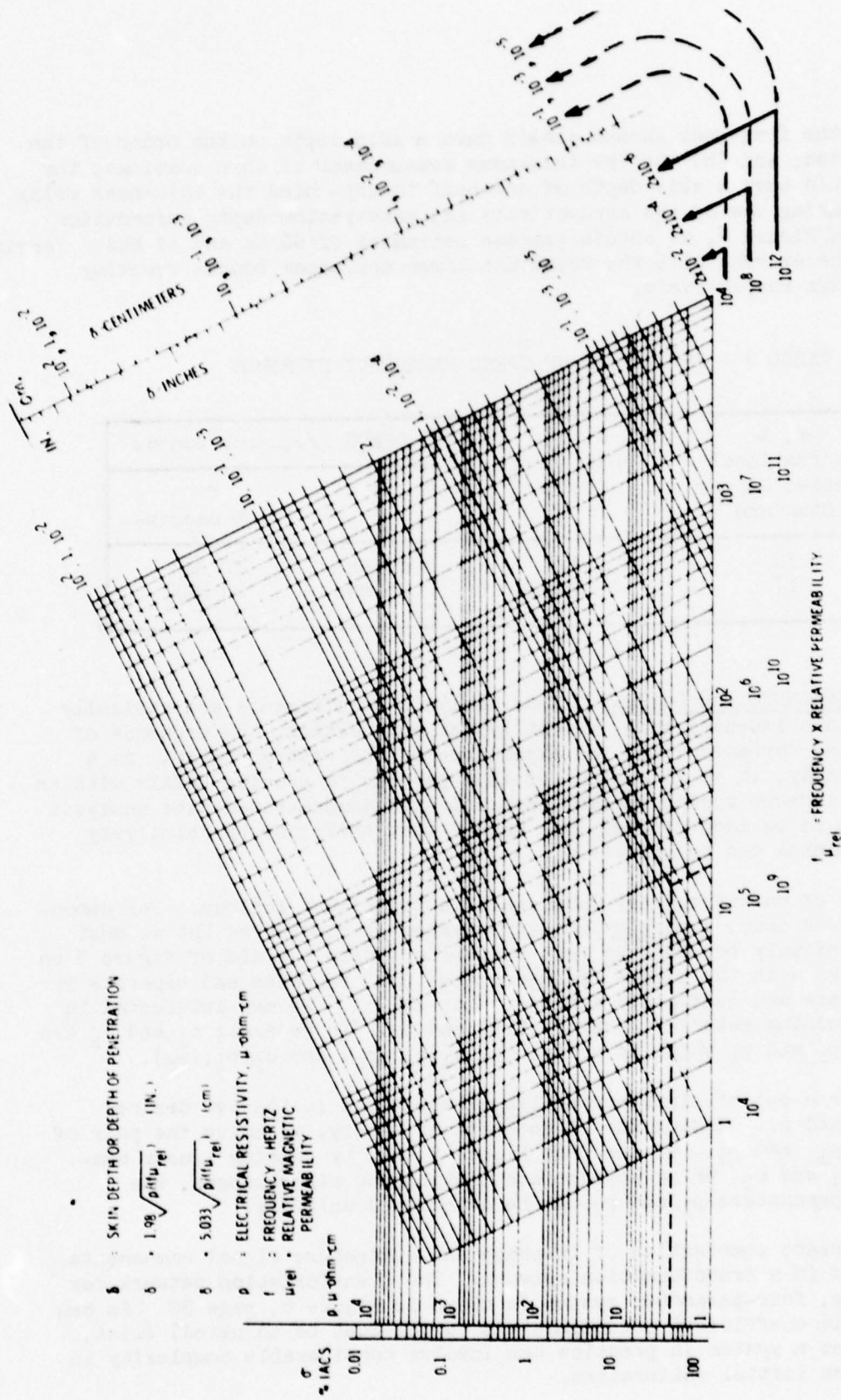
FIGURE 4. NOMOGRAM RELATING MATERIAL CONDUCTIVITY AND SKIN DEPTH
TO THE PRODUCT OF RELATIVE PERMEABILITY AND FREQUENCY

penetration, the frequency chosen should have a skin depth on the order of the thickness tested; and (b) for the thickness measurement of thin coatings, the frequency should have a skin depth of one-half to one-third the thickness being estimated. Making use of the conductivity and penetration depth information of Table 3 and Figure 4, we obtain extreme estimates of 80 Hz and 15 MHz. Margin is added to the extreme with the resultant lower and upper bounds becoming 10 Hz and 20 MHz respectively.

TABLE 3 - ESTIMATION OF GPECS FREQUENCY EXTREMES

	σ, % International Annealed Copper Standard	Skin Depth (inches)	GPECS Frequency Bounds	
			f	f (with margin)
1.	30	0.5	80 Hz	10 Hz
2.	17	0.005	15 MHz	20 MHz

2. <u>DATA ANALYSIS AND DISPLAY</u>. Data analysis requirements are basically determined by the intended eddy current system application, the presence of extraneous noise variables, and the experience of the test operator. As a general philosophy, it is the intent of this program to provide NAVAIR with an advanced eddy current system whereby sophisticated demonstrated data analysis techniques are to be incorporated in a manner that their use by relatively untrained personnel can be effected.

● An example of multifrequency data analysis techniques follows. For demonstration purposes only, a <u>single</u> frequency system is considered but we must discriminate uniquely between <u>two</u> test variables. With the aid of Figure 5 on page 19 we start with the single frequency test coil response and separate it into its in-phase and quadrature components c_1 and c_2. We are interested in uniquely determining material parameters p_1 and p_2. In general, c_1 and c_2 are a function of p_1 and p_2 which is written as $c_1(p_1, p_2)$ and $c_2(p_1, p_2)$.

● We consider a set of simultaneous <u>linear</u> equations in the two desired parameters p_1 and p_2. Making use of determinant theory, we solve the pair of equations for p_1 and p_2. We see from Figure 5 that by summing linear combinations of c_1 and c_2, using appropriate scaling and sign changes, the separation of parameters p_1 and p_2 can be determined uniquely.

● The appropriate combination of in-phase and quadrature signal components is accomplished in a transformation network. The transformation network for a two-frequency, four-parameter system is shown in Figure 6, page 20. As can be seen, some 16 coefficient potentiometers (which must be adjusted) exist, and to implement a system in practice can involve considerable complexity in equipment and/or initial calibration.

NONUNIQUE

UNIQUE

f_i

IN-PHASE COMPONENT — $c_1(p_1,p_2)$

QUADRATURE COMPONENT — $c_2(p_1,p_2)$

Σ → p_1

Σ → p_2
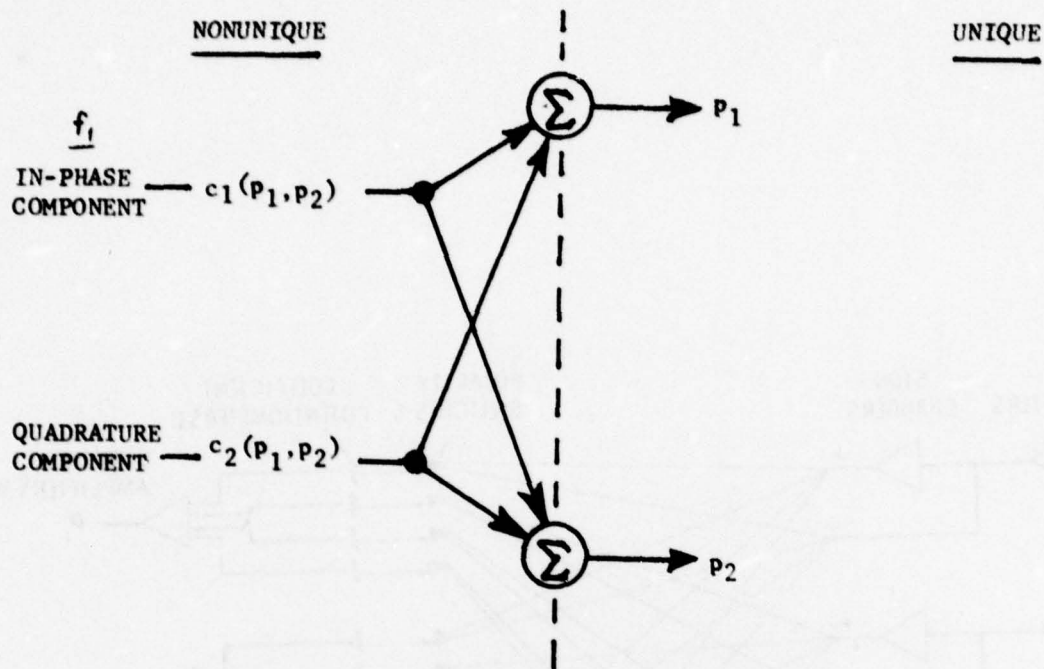
SIMULTANEOUS LINEAR EQUATIONS

$$c_1(p_1,p_2) = a_{11}p_1 + b_{12}p_2$$

$$c_2(p_1,p_2) = a_{21}p_1 + b_{22}p_2$$

$$p_1 = \frac{\begin{vmatrix} c_1 & b_{12} \\ c_2 & b_{22} \end{vmatrix}}{\begin{vmatrix} DET \end{vmatrix}}$$

$$p_2 = \frac{\begin{vmatrix} a_{11} & c_1 \\ a_{21} & c_2 \end{vmatrix}}{\begin{vmatrix} DET \end{vmatrix}}$$

$$\begin{vmatrix} DET \end{vmatrix} = (a_{11}b_{22} - a_{21}b_{12})$$

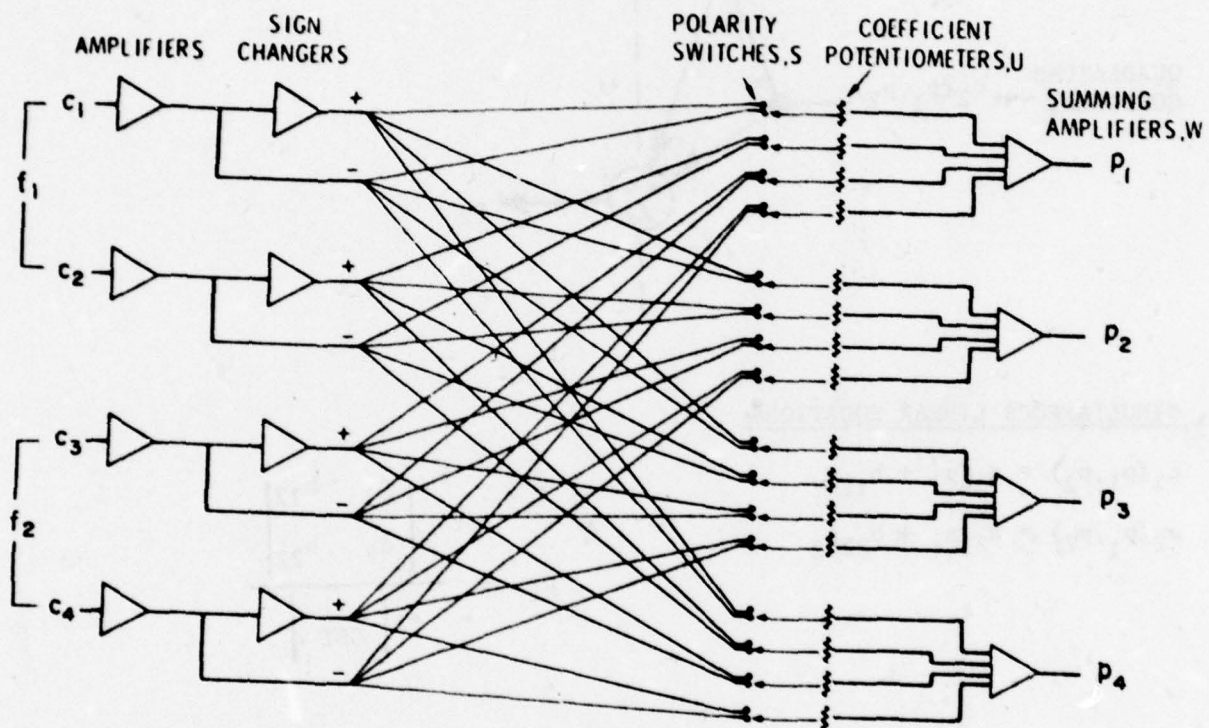FIGURE 5.   PARAMETER DISCRIMINATION METHODOLOGY

19

FIGURE 6.   MULTIFREQUENCY TRANSFORMATION NETWORK FOR A TWO-FREQUENCY
FOUR PARAMETER EDDY CURRENT SYSTEM

● Advantages of a multifrequency approach include the separation of parameters resulting in a uniqueness of the output signal and an increase in measurement precision since the effects of extraneous variables can be minimized. Disadvantages would include an increase in equipment complexity (that is, essentially a 2M-channel eddy current instrument where M is the number of test frequencies), associated electronic complexities with the transformation section, and complexity in overall instrument calibration. In addition, each of the parameters, p_i, that one is interested in must be represented separately in test specimens so that appropriate transformation section adjustments can be achieved.

● Multifrequency technology is a demonstrated technology and systems can be purchased commercially. An example of its capability is shown in Figure 7 on page 22. A four-frequency multifrequency system was implemented for the on-line inspection of cold-drawn steel wire at 20 feet/minute. Figure 7 shows the four single-frequency in-phase or quadrature outputs at 6 KHz, 30 KHz, 150 KHz, and 800 KHz. The lower trace of Figure 7 shows the composite multifrequency output channel derived from a linear combination of the single-frequency channels. The composite channel baseline is significantly cleaner allowing for the reliable detection of defects on the order of 1-2.5 percent. These defect signals are not obvious in the single-frequency channels.

● As has been stated, the development of MFEC for a specific application requires the selection of excitation frequencies and the determination of the coefficients of the terms in the composite equation (i.e., the gain constants, K_{ij}, of the summation amplifiers). Determining the equations that represent the signal used in the composite equation can be a difficult, if not impossible, task. Experiments employing precisely fabricated and controlled material samples are required to calculate the coefficients for each material variable that can cause an eddy current output signal. In many cases, all of the variables are not known, and frequently the range of known variables cannot be defined. Setting the gain factors on MFEC experimental equipment by trial and error can be a tedious and costly process, particularly when more than three frequencies are employed. With so many possible combinations to consider, it is difficult to determine what the optimum parameters should be.

● A statistical method aided by the use of a digital computer has been employed by Battelle-Columbus Laboratories to calculate the gain constants. This technique, based on the concepts of Multiple Linear Regression Analysis (MLRA), is designed so that all of the material variables do not have to be defined. The gain constants of the composite channel are determined from raw data, eliminating the need for tedious experimental studies.

● The inputs to the regression analysis computer program are the values of the eddy current signal voltages obtained simultaneously as the probe coil scans the material of interest. The actual values of the variable of interest are given to the computer to test the validity of the composite equation. A least-squared error criterion is used in the regression technique to provide the coefficients of the optimum composite equation. This composite equation is the best estimator of the variable of interest for the given input signals. Since data can be taken at several frequencies, various combinations can be evaluated quickly and efficiently by the computer.
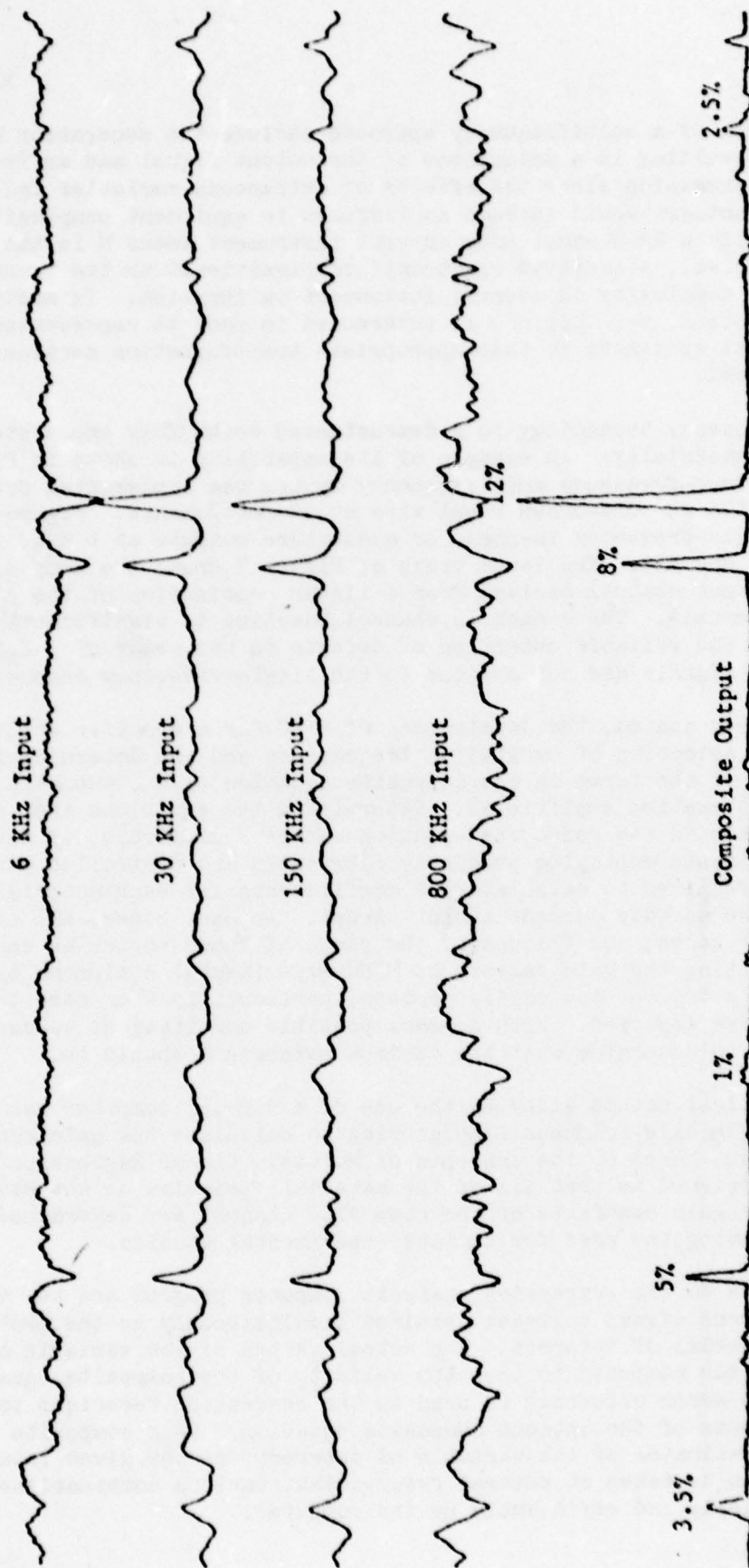
6 KHz Input

30 KHz Input

150 KHz Input

800 KHz Input

Composite Output

2.5%

12%

8%

1%

5%

3.5%

FIGURE 7. MULTIFREQUENCY INSPECTION OF COLD-DRAWN STEEL WIRE

● MLRA assumes a linear relation among the predictive variables:

$$Y = K_0 + K_1 (K1) + \ldots + K_n (Xn)$$

In this predictive function, the independent variables are X1, X2, . . ., Xn. The method of data analysis yields optimum least-squares estimates for the coefficients K_1, K_2, . . ., Kn. After the coefficients are determined, the linear regression formula may then be used to predict the presence or absence of a defect as follows. Suppose that K1, . . ., K6 denote six multifrequency voltage measurements obtained at a location where it is not known whether a defect exists. These six values are used to compute the numerical value of Y using the above equation and the K values obtained by least squares from the learning stage of data analysis. This computed value of Y is next compared with reference value of Y to detect defects. Computed values which exceed the threshold are defects. The extent to which they exceed the threshold is an estimate of their defect depth.

● As an example of the MLRA capability, a method developed by Battelle-Columbus for the measurement of pipe wall thickness is described. Figure 8 on page 24 shows a plot of single-frequency (41 Hz) measured eddy current phase angle versus pipe wall thickness. As can be seen, the scatter in the eddy current data is significant.

● Figure 9, page 25, illustrates the composite multifrequency regression output for a 3-frequency system (41 Hz, 84 Hz, and 338 Hz) versus pipe wall thickness. As is apparent, a significant reduction in data scatter results.

● An average of 20 continuous MFEC measurements for each of the three frequencies was used in the regression analysis to determine the coefficients of the predictive formula for estimation of average wall thickness. The predictive formula derived by the regression analysis was:

$$Y_{av} = -(0.002)V_1 + (0.115)V_2 + (0.229)V_3$$

$$-(0.254)V_4 - (0.078)V_5 - (0.090)V_6 + 0.273$$

The V_i represents the in-phase and quadrature components of the three frequencies and Y_{av} represents the computed wall thickness.

● As an additional example of MLRA capability, consider the nondestructive estimate of case depth on case-hardened steel parts is determined primarily by the surface hardness and depth of the case, and it is important that nondestructive techniques exist for the measurement of these properties.

● Figure 10, page 26, illustrates a Battelle-Columbus designed test coil for the insertion in the steel gear teeth region. The actual diameter of the test coil was on the order of 0.080 inch and the coil excitation frequencies were 2.4 KHz, 20 KHz, and 134 KHz.

● Figure 11, page 27, illustrates a plot of the MFEC regression output versus the depth of the case-hardened surface. The plot indicates a direct proportion relationship between MFEC output and case depth with a certain amount of

FIGURE 8. PLOT OF PHASE ANGLE OF 41 HZ SIGNAL VERSUS
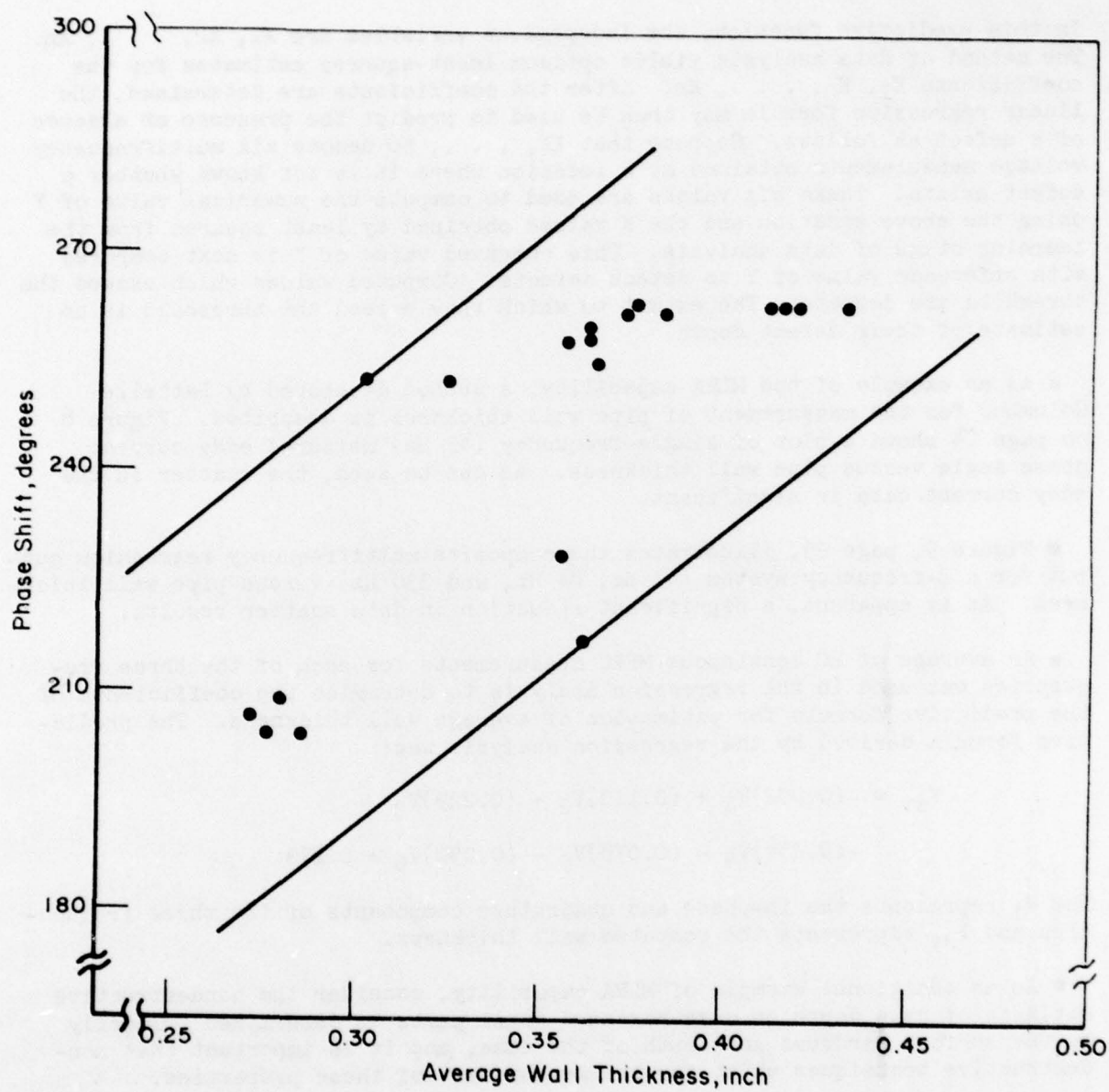ACTUAL WALL THICKNESS

FIGURE 9.   PLOT OF MFEC ESTIMATE OF WALL THICKNESS
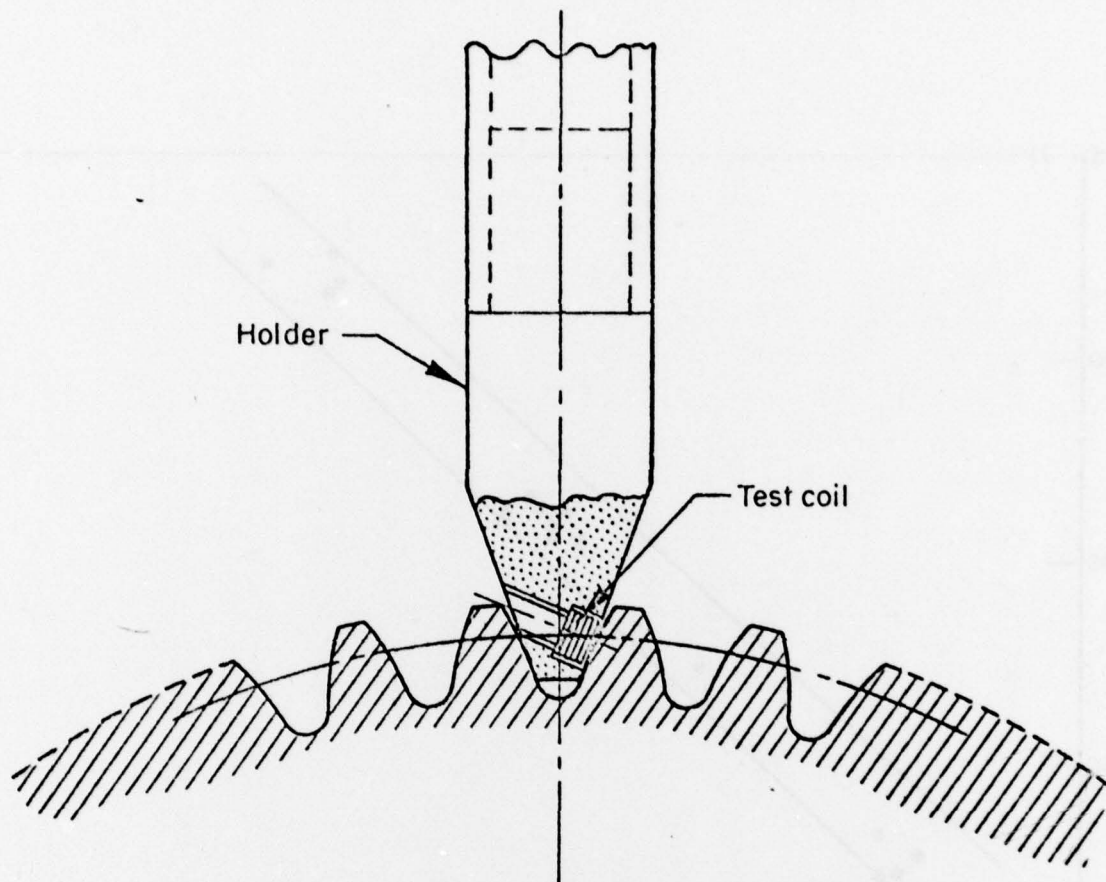VERSUS ACTUAL WALL THICKNESS

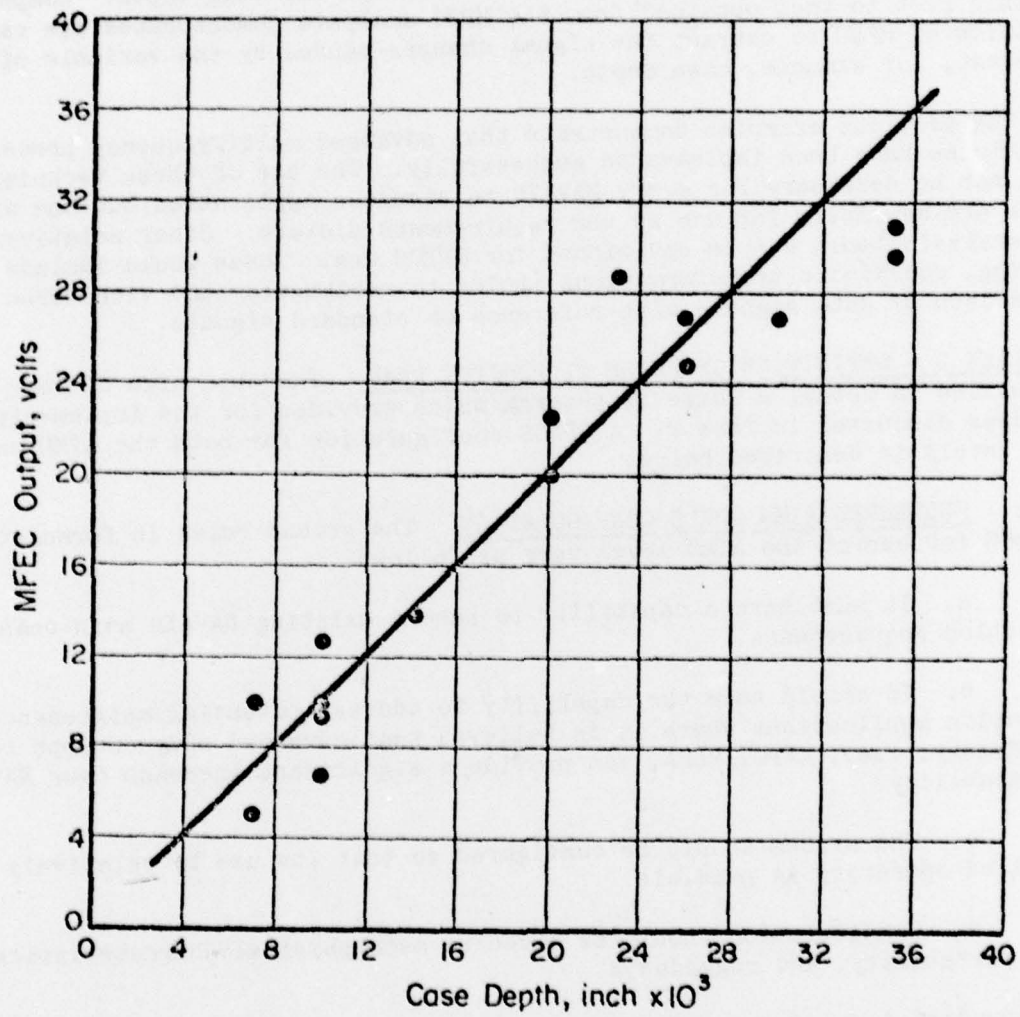FIGURE 10.   EDDY CURRENT TEST COIL FOR INSPECTION OF GEAR TEETH

FIGURE 11. MULTIFREQUENCY EDDY CURRENT COMPOSITE OUTPUT VERSUS CASE DEPTH

scatter about the regression line. The average estimated error in measuring case depth is ±0.003 inch.

● In contrast, Figure 12 on page 29 illustrates a plot of a single-frequency eddy current measurement taken on the same samples. Clearly, there is no apparent correlation between these readings and case depth. Comparison of this plot to that obtained from the MFEC analysis demonstrates the capabilities of MFEC to extract the signal changes caused by the variable of interest, for example, case depth.

● The previous examples demonstrate that advanced multifrequency processing techniques have been implemented successfully. The use of these techniques will not be necessary for every NAVAIR maintenance application but the analysis tools are available for use as the requirements dictate. Other relatively simple analysis tools can be envisioned for GPECS use. These would include data scaling, coordinate transformations (polar to rectangular and vice versa), comparison of data signals with reference or standard signals.

D. TASK 3 - DEFINITION OF PHASE II PROJECT PLAN. The objective of Task 3 is to outline in detail a Phase II program which provides for the implementation of ideas discussed in Task 2. A GPECS configuration for both the AIMD and NARF levels is described below.

1. SUGGESTED AIMD GPECS CONFIGURATION. The ground rules in formulating a GPECS for use at the AIMD level were as follows:

a. It must have a capability to handle existing NAVAIR maintenance inspection requirements.

b. It should have the capability to address potential maintenance inspection applications where it is believed that advanced eddy current testing methodology, i.e., MFEC, MLRA, can provide a significant increase over NAVAIR NDE capability.

c. The system should be configured so that its use by relatively unskilled operators is possible.

d. Consideration should be given to such physical characteristics as size, portability, and ruggedness.

The four divisions of the AIMD GPECS configuration are illustrated schematically in Figure 13, page 30, and are as follows:

(1) System control and data analysis
(2) Eddy current coil/scanner assembly
(3) Data acquisition
(4) Data display.

Some general comments on each of the above items are now considered.

a. System Control and Data Analysis. The key to the feasibility of the GPECS is the programmable instrumentation controller shown in Figure 13.
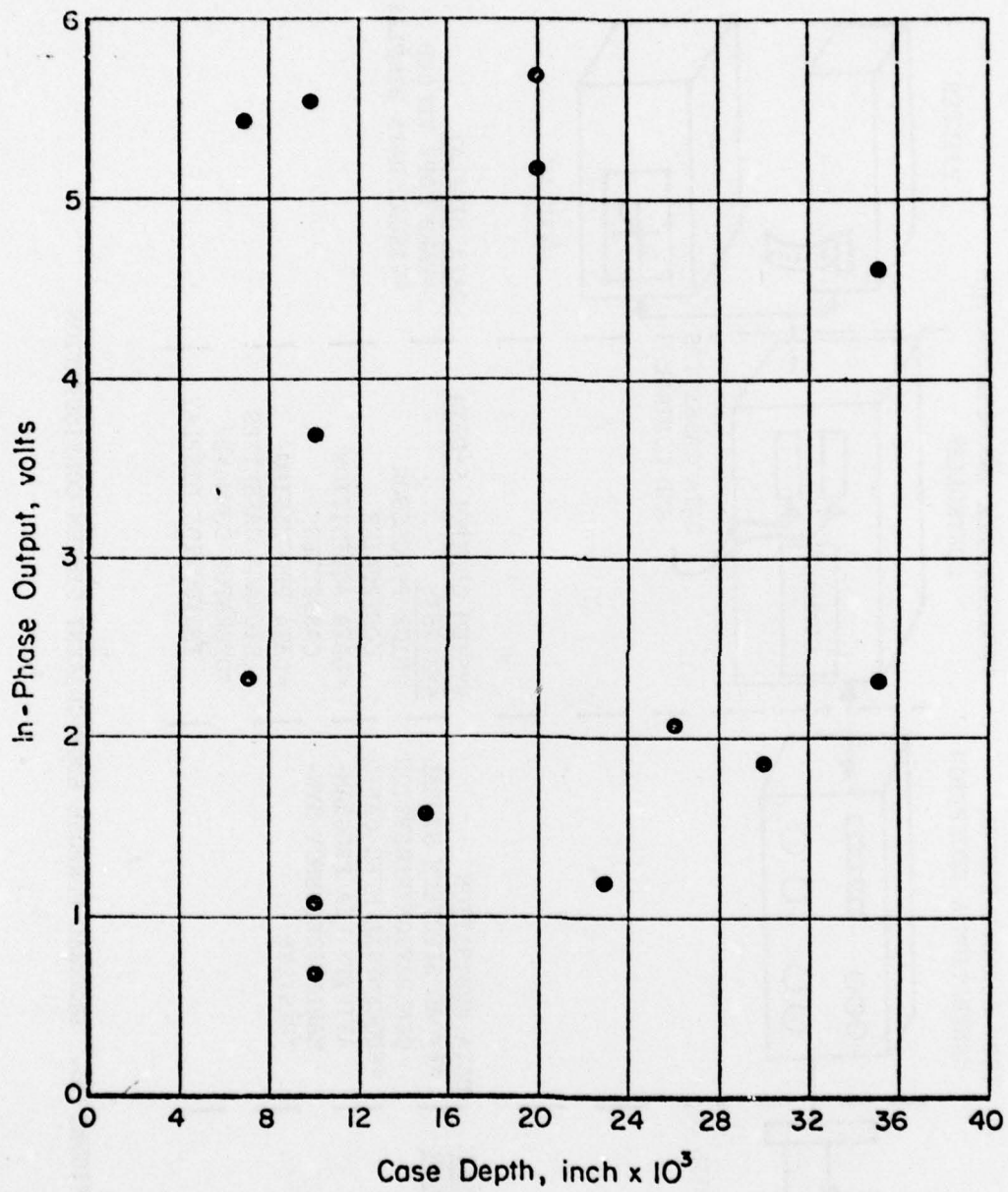
FIGURE 12. EDDY CURRENT SINGLE-FREQUENCY OUTPUT VERSUS CASE DEPTH
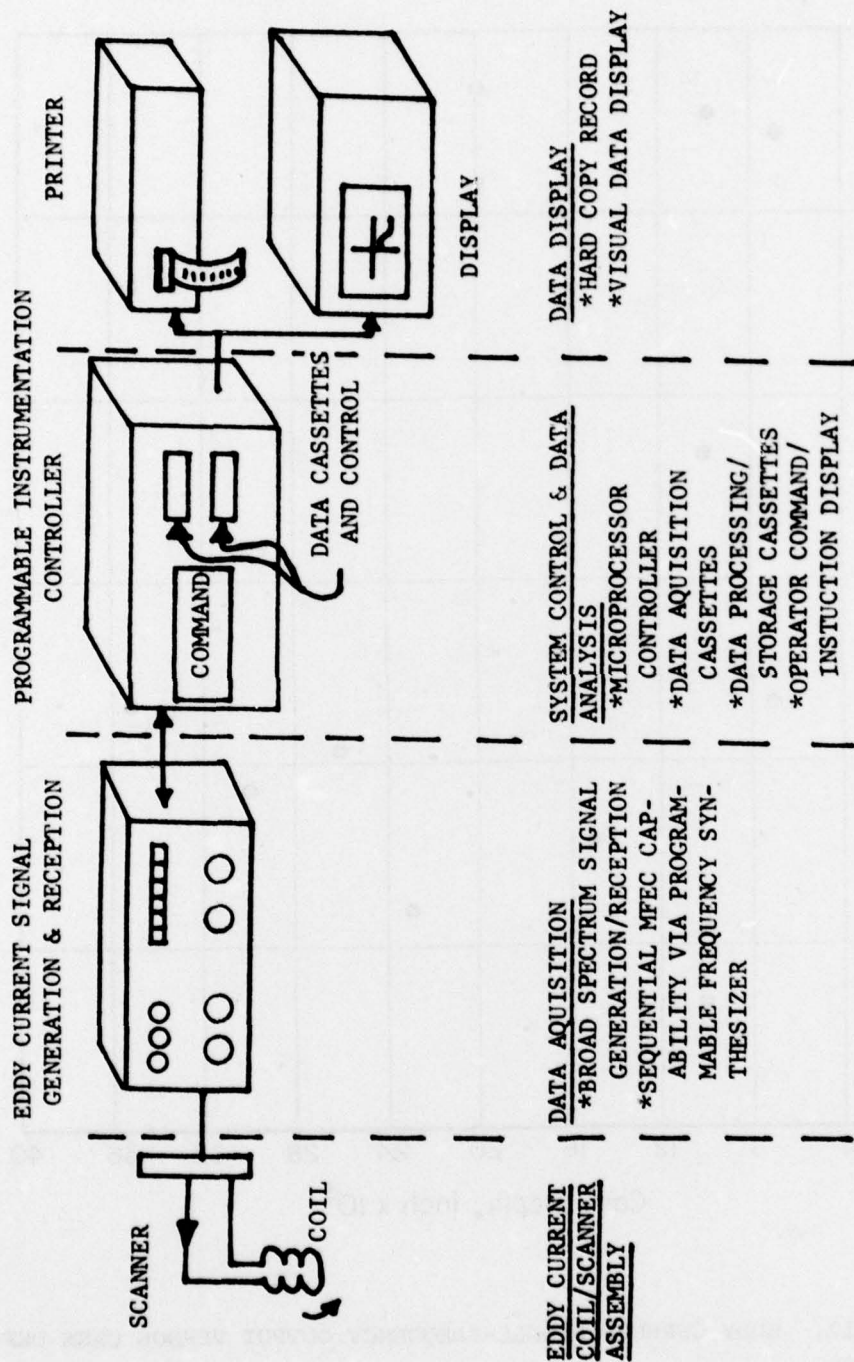
FIGURE 13. GENERAL PURPOSE EDDY CURRENT SYSTEM CONFIGURATION

30

This controller contains a microprocessor for system control and data analysis. Programmed tape cassettes in turn control the microprocessor for particular NAVAIR maintenance eddy current test applications and also provide a medium for permanent data storage. The instrumentation controller would essentially direct all data acquisition in either a single-frequency or multifrequency mode, provide for coil scanner control as necessary, implement required data analysis techniques such as MLRA, and provide control and data for the operator display. Command instructions are also provided on the controller front panel and provide the system operator with a sequenced set of instructions for the particular test application at hand. Each NAVAIR test application would have its own control cassette. The data cassette can be used for permanent data storage and long term maintenance histories can be monitored.

      b. <u>Eddy Current Coil/Scanner Assembly</u>. The eddy current coil/scanner assembly is considered a general design area. Specific coil requirements, as discussed previously, will be determined by the particular eddy current test application, and rational design of the coil must rely on detailed computer studies. The GPECS will be able to accommodate both differential and absolute type coils.

• The need for a scanner assembly is not universal and will be determined by particular test applications such as (1) the need to inspect large surface areas in a reliable, systematic manner, or (2) the lack of manual accessibility in certain inspection situations such as bolt hole inspection. In general, the test part geometry will determine the mechanical requirements of the scanner. It should be noted that the digital nature of the system controller makes it ideally suited to the task of controlling and monitoring both simple and complex scanner mechanisms.

• A very important scanner consideration is scan rate. This can have direct impact on the GPECS requirements in that it will be limited by the maximum system bandwidth. If small discontinuities, for example, surface cracks on the inside of a bolt hole, are scanned too rapidly, the eddy current system bandwidth may be inadequate for necessary signal buildup to occur, prohibiting the detection of the surface crack. Too large a bandwidth will increase the thermal noise in the eddy current system essentially resulting in a decrease in ultimate sensitivity. Decreasing scan rates to accommodate a given system bandwidth imply longer inspection times. Thus when specifying the scan rate, trade-offs must be considered between inspection speed and the complexity of the eddy current electronics. Overall scanner requirements must await further definition during the Phase II effort.

      c. <u>Data Acquisition</u>. The data acquisition section of the GPECS must be concerned with eddy current coil excitation, signal conditioning, and signal measurement. The specification of this part of the system is dictated by the need for a broad operating frequency range in order that anticipated NAVAIR inspection applications be met and the necessity for generating more than one frequency in order to perform multifrequency eddy current testing.

• Conventional multifrequency systems excite the test coil simultaneously at more than one frequency. This approach requires parallel duplication of

signal oscillators, filter networks, signal amplifiers and detectors. An
alternative to utilizing several signal frequency data channels in parallel
is to generate the required number of frequencies in a sequential manner.

● Frequency synthesizers which are both frequency and amplitude programmable
are commercially available. A typical tunable frequency range is 1 Hz to
20 MHz, with a frequency stability of 10 parts per million. These synthesizers
may be too general purpose for the eddy current application at hand, but their
existence clearly demonstrates that the technology exists for programmable
signal generation of sequential multiple frequencies.

● All functions of the data acquisition section are to be remotely controlled
by the system controller. This feature will eliminate the need for the opera-
tor to make any adjustments or set any knobs. For a given testing situation,
such parameters as which frequencies, how many frequencies gain settings, and
filtering requirements will be programmed by the system control device de-
scribed in the previous section.

        d. <u>Data Display</u>. AIMD display capabilities are structured such that
information necessary to assist the GPECS operator in decision making is
presented in its simplest form. As an example, simple GO/NO-GO panel lights
can be mounted on the programmable instrumentation controller for eddy current
tests involving simple two-state comparative testing.

● More complex eddy current tests would require the use of x-y storage
oscilloscopes (Memory-Scope) or printers for hard copy data records. Digital
displays for the viewing of quantitative test results are also necessary.

      2. <u>SUGGESTED NARF GPECS CONFIGURATION</u>. The NARF system will consist of
the GPECS plus additional system interactive devices and data storage medium.
The additional hardware include: (1) Alphanumeric display and keyboard, (2)
a line printer, and (3) bulk data storage devices such as floppy discs.

● At the NARF maintenance level, the capability must exist to program the
GPEC control cassettes as well as make use of the entire GPECS for the
development and checkout eddy current test procedures.

● Sufficient computing capability will be in the AIMD GPECS programmable
instrumentation controller so that direct interfacing at the NARF maintenance
level with the necessary interactive devices can be accomplished.

      3. <u>SUGGESTED PHASE II PLAN</u>. A recommended Phase II plan is outlined in
Table 4, page 33. Four basic tasks can be identified. Task I selects four
NAVAIR eddy current test applications which are to be used as a basis for the
GPECS definition and initial system verification. It is suggested that a mix
of applications be chosen which will demonstrate the GPECS overall capability
and superiority. Also some existing tests can be chosen so that comparisons
between the GPECS results and present AIMD eddy current can be made. Recom-
mended test applications include (a) plasma spray coating thickness measure-
ment, (b) heat damage, (c) corrosion detection on underside surfaces, and
(d) jet-engine blade/vane integrity. The choice of plasma spray coating

thickness measurements and corrosion detection on underside surfaces represent extremes in GPECS frequency of operation and represent existing NAVAIR NDE maintenance requirements for which AIMD eddy current capability is nonexistent or has not been demonstrated in a successful manner. The measurement of heat damage represents a situation for which a direct comparison can be made between present AIMD eddy current measurement capability and GPECS results. Jet-engine blade/vane integrity represents a demonstrated NAVAIR eddy current maintenance problem area, i.e., F-14 engine, and would probably emphasize the coil/scanner aspects of the GPECS.

TABLE 4 - PHASE II PROGRAM PLAN

1. Selection of NAVAIR Maintenance Inspection Problems

    a. Define Four Eddy Current Application Areas

        - Plasma Spray Coating Thickness Measurement
        - Heat Damage
        - Corrosion Detection on Underside Surfaces
        - Jet-Engine Blade/Vane Integrity

    b. Determine Existing NAVAIR Eddy Current Approaches

    c. Define Extraneous Test Variables

2. Detailed Eddy Current Test Design

    a. Conduct a Computer Parametric Study to Determine Optimum Coil Design and Test Frequency or Frequencies

3. GPECS Detailed Definition, Design, and Integration

    a. Definition/Design and Assembly

        - Data Acquisition
        - Computer Interface and Control, Processing
        - Display
        - Coil Scanner

    b. System Integration

        - Integrate Elements
        - Checkout

4. GPECS Laboratory Evaluation of NAVAIR Provided Test Specimens

    a. Detailed System Laboratory Evaluation

    b. Comparison with AIMD Results

    c. Demonstration for NARF/AIMD Personnel

● Once the test applications are agreed upon, a detailed investigation of existing AIMD eddy current test approaches and field results is suggested. At this time a definition of test object geometry and potential extraneous test variables can be identified. It is expected that additional field trips to AIMD facilities will be necessary.

● Using specific information derived from Task 1 and maintaining a general awareness of additional potential applications described initially in Table 2, computer parametric studies will be conducted to determine optimum test coil configurations and confirm the estimated frequency bounds on the overall GPECS.

● Task 3 is concerned with the detailed definition, design, and assembly of subsystem elements and their final integration and checkout at the system level. In reviewing existing and anticipated AIMD eddy current applications and present day electronic technology, it has been concluded that no component developmental effort is necessary for the system electronics. What is envisioned is the use of essentially off-the-shelf components or electronic test instrumentation with equipment integration at the subsystem level followed by overall system interfacing.

● Task 4 is a critical laboratory evaluation of the GPECS using representative test samples for each of the agreed upon application areas. The improved general purpose eddy current system capability incorporating the multifrequency technology as necessary can be compared directly with existing AIMD results (where they exist). The early phase of this task could also be used to obtain preliminary feedback information in order that the necessary system modifications be made. During this task, it is highly recommended that representatives from NARF and AIMD witness the use of the system so that critical comments as to its use in the field by field personnel can be identified.

E. TASK 4 - PHASE III PROGRAM OUTLINE. The Phase III objective is to develop a field compatible version of the basic GPECS developed in Phase II. In general, three tasks can be identified: (1) a development of the lab prototype GPECS for use in the NAVAIR maintenance environment, (2) preparation of operations and maintenance manuals, and (3) field evaluation of the system.

● Repackaging of the laboratory system is the most cost effective way to develop the field prototype unit. Consideration here must be given to environmental factors and the handling and use by field personnel. Verification of the field prototype unit capabilities in the laboratory can be considered by repeating the series of experiments described in the Phase II program plan.

● Task 2 involves the detailed documentation of the GPECS. This would include the preparation of system operation and maintenance manuals, equipment checkout procedures, schematics, and anticipated spare part requirements. Also necessary are the preparation of detailed eddy current maintenace application test procedures.

● In Task 3, extensive AIMD field evaluation of the field prototype GPECS is suggested. Battelle-Columbus staff members will take the system on site to AIMD or NARF locations and assist in the training and education of

maintenance personnel. Use of the system can be demonstrated on actual inspection problems with maintenance technicians providing comments as to the system's effectiveness and ease of operation.

DISTRIBUTION LIST

NAVAIRENGCEN
1115
92A1
92A12   (2)
92713
92724   (20)
9011

NAVAIRSYSCOM
AIR-340E   (2)
AIR-5343   (2)
AIR-411   (2)
AIR-5203   (2)
NAVAIRDEVCEN
60633   (2)

REVISION LIST

REVISION	PAGES AFFECTED	DATE OF REVISION